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# Appendix Q

## NIST'S WORKING HYPOTHESIS FOR COLLAPSE OF THE WTC TOWERS

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In response to the terrorist attacks of September 11, 2001, and the resulting collapse of the World Trade Center (WTC) buildings, the National Institute of Standards and Technology (NIST) has been investigating possible collapse scenarios. Establishing the sequence of events that led to the towers collapsing is important in determining which factors allowed the buildings to hold up for as long as they did without collapsing, and which factors, if any, could have delayed or prevented the collapse of the WTC towers. Understanding these factors will provide valuable information on which to base recommendations for improvements to buildings practices, standards, and codes that may be warranted.

### Q.1 OBJECTIVES

The objectives of the NIST analysis are:

- Establish how and why the WTC towers collapsed after the aircraft impact, i.e., the 'triggering event'
- Determine the most probable collapse sequence
- Identify the factors that have the strongest influence on the most probable sequence

### Q.2 APPROACH

To identify the most probable of the technically possible collapse sequences, NIST is adopting an approach that combines mathematical modeling, well-established statistical and probability based analysis methods, laboratory experiments, and analysis of photographic and video evidence. The approach accounts for variations in models, input parameters, analyses, and observed events. It allows for

#### Background

NIST has estimated that 17,400 occupants ( $\pm 1,200$ ) were present in the WTC towers on the morning of September 11, 2001, about equally divided between the two buildings (8,900 in WTC 1 and 8,540 in WTC 2). 2,159 building occupants and an additional 433 first responders, including security guards, were reported to have lost their lives that day. This does not include aircraft passengers and crew or bystanders.

Approximately 87percent of the WTC tower occupants were able to evacuate successfully. More than 99 percent of occupants below the crash impact areas had sufficient time prior to collapse of the buildings to safely evacuate. WTC 1 stood for one hour and 43 min after impact; WTC 2 collapsed 56 min after it was struck.

Preliminary estimates indicate that about 20 percent or more of those in the WTC towers who lost their lives may have been alive in the buildings just prior to their collapse. This includes nearly all of the first responders and 76 building occupants below the floors of impact. There were 72 fatalities reported in WTC 1 and 4 fatalities reported in WTC 2, not including first responders, below the floors of impact.

Buildings are not designed to withstand the impact of fuel-laden commercial airliners. However, Port Authority documents indicate that the impact of a Boeing 707 flying at 600 mph and possibly crashing into the 80th floor had been analyzed during the design of the WTC towers in February/March 1964. While NIST has not found evidence of the analysis, the documents state that such a collision would result in localized damage only, and that it would not cause collapse or substantial damage to the WTC towers. The effect of fires due to jet fuel dispersion and ignition of building contents was not considered in the 1964 analysis. Loss of life in the immediate area of aircraft impact was anticipated, but loss of life from fire and smoke was not considered.

evaluation and comparison of possible collapse hypotheses based on different damage states, fire paths, and structural responses to determine the following:

1. The most probable sequence of events from the moment of aircraft impact until the initiation of global building collapse;
2. How and why WTC 1 stood nearly twice as long as WTC 2 before collapsing (103 min versus 56 min), though they were hit by virtually identical aircraft;
3. What factors, if any, could have delayed or prevented the collapse of the WTC towers.

### **Q.3 FACTORS TO EVALUATE THE WORKING HYPOTHESIS**

In further evaluating the working hypothesis for the collapse of the WTC towers, NIST is considering the following factors:

- The relative contributions of aircraft impact damage and subsequent fires
- How safe each building was immediately after aircraft impact but before fire weakened the structures, i.e., to what extent the capacity of the buildings to carry design loads<sup>1</sup> was reduced
- Relative roles of the perimeter and core columns<sup>2</sup> and the composite floor system,<sup>3</sup> including connections
- The role played by fireproofing, especially the extent to which fireproofing may have been damaged due to aircraft impact
- Whether the undamaged towers would have remained standing in a “maximum credible fire”<sup>4</sup>
- The role compartmentation (i.e., areas divided by fire-rated walls) may have played, i.e., what would have happened if the floors had been separated into 7,500 or 10,000 ft<sup>2</sup> compartments with 1 h fire-rated partition walls or separations

### **Q.4 THE WORKING HYPOTHESIS**

NIST has developed a working hypothesis to explain the sequence of events from aircraft impact until the initiation of global structural collapse. This hypothesis will be further refined based on the results of

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<sup>1</sup> The design of the WTC towers was governed by gravity and lateral wind loads.

<sup>2</sup> The perimeter columns were designed to carry both gravity and wind forces and acted together as a framed-tube system. The core columns were designed to carry only gravity loads and not required to provide frame action.

<sup>3</sup> The composite floor truss system, which included long-span open-web bar joist elements, was designed to carry floor loads to the supporting core and perimeter columns. It also acted as a diaphragm that distributed wind forces to the perimeter columns of the framed-tube system and provided lateral stability to the perimeter columns.

<sup>4</sup> A maximum credible fire for the WTC towers is assumed to have the following characteristics: the sprinkler system is compromised, overwhelmed, or not present; there is no active firefighting; combustible building contents averaging 10 psf (in the range of about 5 to 20 psf for conventional office buildings); floor-to-floor fire spread to next upper floor at 30 or 60 min; and ventilation from windows broken by fire and a total of 50 ft<sup>2</sup> of air leakage between floors.

NIST's continuing comprehensive analyses to identify specific load redistribution paths and damage scenarios that are possible for each building, from which the most probable collapse sequence will be identified. NIST welcomes comments from technical experts and the public on the working hypothesis.

NIST's working hypothesis is based on analysis of the available evidence and data, consideration of a range of hypotheses (including those postulated publicly by experts), and a newly enhanced understanding of structural and fire behavior. It is consistent with all current evidence held by NIST, including photographs and videos, eyewitness accounts, and emergency communication records. NIST's analysis allows for different sequences of events and different possible event paths for each building.

To accommodate the aircraft impact and subsequent fire damage, the structure redistributed loads from structural element to structural element via redundant load paths and maintained overall structural stability. Structural collapse began when the structure was not able to redistribute loads any further. The working hypothesis addresses the following chronological sequence of major events; specific load redistribution paths and damage scenarios are currently under analysis:

1. Aircraft impact damage to perimeter columns with redistribution of column loads to adjacent perimeter columns and to the core columns via the hat truss;
2. After breaching the building's exterior, the aircraft continued to penetrate into the buildings, damaging core columns with redistribution of column loads to other intact core and perimeter columns via the hat truss and floor systems;
3. The subsequent fires, influenced by post-impact condition of the fireproofing, further weakened columns and floor systems (including those that had been damaged by aircraft impact), triggering additional local failures that ultimately led to column instability;
4. Initiation and horizontal progression of column instability ensued when redistributing loads could not be accommodated any further. The collapses then ensued.

#### **Role of the Hat Truss System**

The purpose of the hat truss was to support gravity and wind loads on the antenna. It was not designed to resist lateral forces on the towers, and, in an undamaged state, it did not have a significant role in carrying gravity loads. Lateral loads due to wind were distributed to the framed-tube system via diaphragm action of the floor system. The hat truss was connected to each perimeter face at only four points, all at the same level (at the 108th floor just below the concrete floor slab). The 47 core columns were connected to diagonal elements, heavier transfer beams, or smaller beam elements in the hat truss. Most of the core columns extended to the roof level, but four core columns, which were only minimally connected to the hat truss, terminated at floor 110. The hat truss provided minimal redistribution of loads (less than 10 percent) from perimeter columns to core columns. Most of the load redistributed due to aircraft impact damage occurred on the external face through vierendeel action.

### **Aircraft Impact Damage to Perimeter Columns**

Initially, the WTC towers withstood the impact virtually identical aircraft. Based on video that NIST has obtained, it is known that WTC 2, which collapsed first and in about half the time as WTC 1, vibrated for over 4 min at an oscillation rate nearly equal to that measured for the undamaged building after it was struck, indicating that the buildings were continuing to respond normally. The lightly damped (about 1.2 percent of critical damping) oscillation had a maximum amplitude of approximately 20 in. at the roof

level, where sway was about 3 ft to 4 ft under design wind conditions. Based on this information, structural damage to perimeter columns as a result of aircraft impact of the framed-tube system appears to have played a minimal role in initiating the collapse. Perimeter column bowing prior to collapse occurred on other faces (i.e., fire floors on the south face of WTC 1 and east face of WTC 2) that were not severed by the aircraft.

### **Aircraft Impact Damage to Core Columns**

The core columns were designed to carry only gravity loads and not required to provide frame action. The aircraft trajectory at impact suggests damage to the core columns occurred as follows:

**WTC 1**—The aircraft was traveling about 450 mph and hit the tower near the center of the north face damaging floors 93 to 99. The aircraft fully entered the core area and severed or damaged central core columns in the north-south direction. Aircraft and building debris accumulated in the remaining core area and south-side floor areas as contents were displaced from the point of impact.

**WTC 2**—The aircraft was traveling about 550 mph and hit the tower near the southeast corner of the building damaging floors 77 to 85. Core columns to the south and east were severed or damaged. Aircraft and building debris accumulated in the core area and floor areas to the east and north.

Severed core columns redistributed their loads in three ways, depending on how many and which core columns were severed.

1. Isolated core columns were severed. Severed column and tributary floor loads at and above the point of impact were redistributed locally at each floor to adjacent intact core columns via core floor framing. This was limited by shear/bending capacity of floor-framing connections to adjacent columns.
2. Critical (e.g., corner) core columns and/or several other core columns were severed. The severed column and tributary floor loads, at and above impact floors, redistributed to intact core columns via the hat truss. Significant hat truss deflections may have occurred if there was adequate connection capacity since the severed core columns and the associated floors were hanging from the hat truss which was not designed to carry such loads. This was limited by the tensile capacity of bolted splices in the severed core columns, tensile/compression capacity of hat truss members, and tensile capacity of column connections to the hat truss.
3. Extent of core column failures precluded redistribution through the hat truss and/or exceeded redistribution capacity of the hat truss: severed column and associated floor loads, at and above floors of impact, redistributed to intact core and perimeter columns via the core and composite truss floor system. Floors were subjected to combined bending and diaphragm action (e.g., consider the scenario of no core columns in the floor span direction to visualize this action). The overall capacity of the floors was limited by shear capacity of floor-to-column connections (including perimeter columns) and tensile/bending capacity of composite truss floor connections to core or perimeter columns. Significant sagging of the hat truss system may have occurred if its capacity was exceeded.

## Relative Roles of Fires and Aircraft Impact

Fires played a major role in collapse initiation. The tower structures withstood the initial aircraft impacts and remained stable. While aircraft impact damage did not, by itself, initiate building collapse, it had the following harmful effects that then contributed greatly to the subsequent fires:

- Compromised the sprinkler and water supply systems,
- Dispersed jet fuel and ignited building contents over large areas,
- Created large accumulations of combustible matter containing aircraft and building contents,
- Increased air supply into the buildings (through broken windows and holes in the sides of the buildings, and between floors due to damaged floors, vertical shafts, and columns) permitted significantly higher energy release rates than would normally be seen in ventilation limited building fires, allowing the fires to spread rapidly within and between floors, and
- Damaged ceilings enabling “unabated” heat transport over the floor-to-ceiling partition walls and to the floor trusses, spandrels, and tops of columns.

The jet fuel, which ignited the fires, was mostly consumed within the first few minutes after impact. The fires that burned for almost the entire time that the buildings remained standing were due mainly to burning building contents and, to a lesser extent, aircraft contents, not jet fuel.

## Thermal Effects on Columns and Floors

Some floors in WTC 2 experienced partial collapse due to aircraft impact. For example, partially collapsed floor slabs were visible on the east and north faces. This included failures at the edges with perimeter columns causing floor edge sagging. There is no visible evidence of hanging floors in WTC 1.

- Fires may have had the following thermal effects: core columns and core floors may have been further weakened, with reduced ability to carry and/or redistribute load, causing such loads to be redistributed to other core and perimeter columns consistent with the residual reserve capacities of these columns and the transfer mechanisms (i.e., hat truss and floor system).
- The floor system may have been further weakened, either along the span of the floor system or localized at connections with columns. The weakening floor system may have pulled the perimeter columns inward (observed on the south face of WTC 1 and the east face of WTC 2 minutes prior to building collapse) and then initiated connection failures at perimeter or core columns.

### Role of Fireproofing

The post-impact condition of the fireproofing played a key role in the structural response to fires. The post-impact condition of the fireproofing depends on the condition of the fireproofing prior to aircraft impact and the extent to which fireproofing was damaged due to aircraft impact. The fire-affected floors in WTC 1 had, in general, upgraded or thicker fireproofing (1.5 in. specified) while, in general, those in WTC 2 did not have upgraded fireproofing (0.5 in. specified).

- Perimeter columns may have been further weakened, with reduced ability to carry loads. Thermal effects could also cause inward bowing of perimeter columns due to differential temperatures between the inner and outer faces of the columns. The loads that could no longer be carried by the weakened columns would have been redistributed to adjacent perimeter columns.

### **Column Instability and Collapse Initiation**

The perimeter columns were designed as part of a framed-tube system to carry both gravity and wind forces. Instability of perimeter columns resulted from a combination of (1) redistributed loads from the core columns via the floor system and possibly the hat truss, (2) inward bowing due to thermally weakened and sagging floors, (3) increased unsupported length due to failed floors, and (4) thermal effects directly on the perimeter columns.

The instability of a few perimeter columns spread instability across the entire face and around the corners just before or during collapse initiation. The initiation or spread of perimeter column instability also may have been facilitated by the hoop stress demand on the framed-tube system exceeding the capacity of the spandrels (horizontal steel plates) that tied the perimeter columns together (e.g., at the northeast corner of WTC 2).

The initiation of global collapse for both towers was first observed by the tilting of the sections above the impact regions of both WTC towers. The top section of WTC 1 rotated to the south (observed via antenna tilting in a video recording) and the top of WTC 2 rotated to the east and south and twisted in a counterclockwise motion. The primary direction of tilt of each tower was around the weaker axis of the core (north-south for WTC 1 and east-west for WTC 2). The rigid body rotation associated with the tilting and the propagation of column instability are synchronous processes that initiated global collapse. The rigid body rotation may have caused forces such as shear and torsion to spread the column instability laterally.

## **Q.5 ISSUES STILL BEING INVESTIGATED**

Over the next few months, NIST will continue to investigate the following technical issues and modify its working hypothesis as needed. Findings on these issues will be included in the final report.

- Aircraft impact damage to structural components, fireproofing, and hat truss connections.
- Distribution of aircraft/building contents.
- Thermal effects on core columns and core floors, especially extent of fires and growth history.
- Thermal effects on welded perimeter columns, especially temperature gradients on columns.
- Extent of load redistribution to intact core columns and their reserve capacity to accommodate thermal loads.

- Capacity of hat truss connections to perimeter columns, especially to meet the demands of aircraft impact and any torsional effects.
- Capacity of hat truss to accommodate the load redistribution from severed columns.
- Capacity of bolted splices in the severed core columns to carry loads to the hat truss.
- Relative magnitude of the load redistribution provided by the local core floor, hat truss, and the core-truss floor system for each tower.
- Axial/shear/bending capacity of floor connections to core and perimeter columns.
- Effect of localized fires on floor truss connections.
- Mechanisms to propagate instability laterally in the perimeter columns (e.g., shear and torsion forces induced by a rigid body movement)
- Capacity of spandrels, including splices, to carry shear transfer in the framed-tube system, especially at the corners.
- Role of bolted splices on instability of perimeter columns.
- Outward bowing of perimeter columns due to thermal expansion of floors.
- Effect of uneven floor thermal expansion on perimeter column instability due to potential biaxial bending.
- Comparison and reconciliation of working hypothesis with observed facts (photographs and videos, eyewitness accounts, emergency communication records).
- Examination of other possible or probable hypotheses.

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